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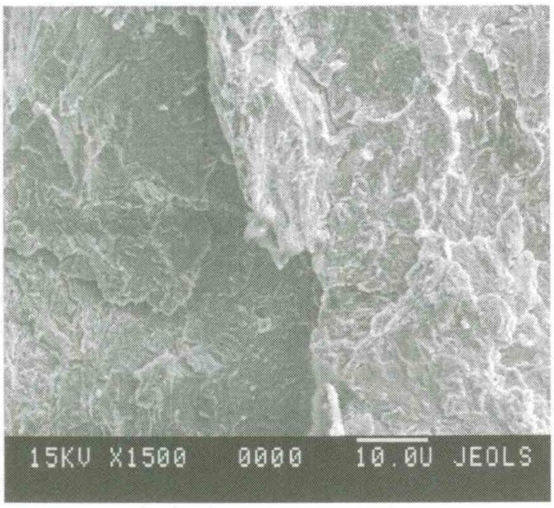

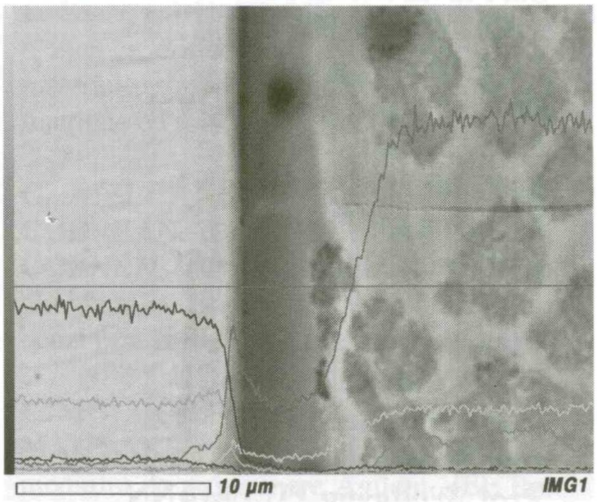

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FUNCTION APPROXIMATION FOR THE HYSTERESIS OF FLUIDIC MUSCLES

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Abstract. Numerous researchers have investigated the relationship of the force, length and pressure to find a good approximation and theoretical approach for the equation of force generated by pneumatic artificial muscles (PAMs). Some of them report several mathematical models, but significant differences have been noticed between the theoretical and experimental results. Accordingly we have generated and introduced a new model and algorithm that gives us simple yet accurate description of this actuator. This paper presents this new function approximation for the hysteresis of Fluidic Muscles manufactured by Festo.

Keywords: Pneumatic Artificial Muscle, Force Equation, Matlab, Genetic Algorithm

1. Introduction

Many researchers have tried to find an actuator similar to human muscles. The most promising actuator in this field of research is undoubtedly the McKibben pneumatic muscle actuator. The McKibben muscle was invented in the 1950's by physician Joseph L. McKibben to help the movement of polio patients and to motorize pneumatic arm orthotics. There exist several types of artificial muscles that are based on the use of rubber or some similar elastic materials, such as the McKibben muscle, the Rubbertuator made by Bridgestone company, Air Muscle made by Shadow Robot company, Fluid Muscle made by Festo company, Pleated PAM developed by Vrije University of Brussel, ROMAC (RObotic Muscle ACtuator), Yarlott and Kukolj PAM and some others [1, 2].

A pneumatic actuator consists of an internal rubber bladder surrounded by a braided shell with flexible yet nonextensible threads according to a helical weaving that is attached at either ends. When inflated, the internal bladder tends to expand, with a consequent increase in the angle between the helical woven fibres of the braid and the axis of the tube and a decrease in axial length [3].

The layout of this paper is as follows. Section 2 (Materials and Methods) is devoted to demonstrate the model of force as a function of pressure and length (contraction). Section 3 (Experimental Results) presents several experimental results and finally, section 4 (Conclusions and Future Work) gives the investigations we plan.

Fluidic Muscles DMSP-10-250N-RM-RM (with inner diameter of 10 mm and initial length of 250 mm), DMSP-20-200N-RM-RM (with inner diameter of 20 mm and initial length of 200 mm) and DMSP-20-400N-RM-RM (with inner diameter of 20 mm and initial length of 400 mm) produced by Festo company were selected for our study.

2. Materials and Methods

The general behaviour of PAM with regard to shape, contraction and tensile force when inflated depends on the geometry of the inner elastic part and of the braid at rest (Figure 1), and on the materials used [1].

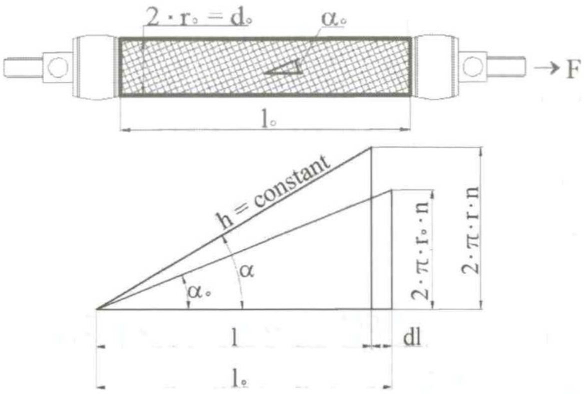

Figure 1 Geometry parameters of PAM

On the basis of [4], [5] and Figure 1, the force can be calculated:

$$F = -p \cdot \frac{dV}{dl} \tag{1}$$

$$2 \cdot p \cdot \pi \cdot r \cdot l \cdot dr - p \cdot \pi \cdot r^2 \cdot (-dl) - F \cdot (-dl) = 0 \tag{2}$$

$$F = -2 \cdot p \cdot \pi \cdot r \cdot l \cdot \frac{dr}{dl} - p \cdot \pi \cdot r^2 \tag{3}$$

$$\cos\alpha_0 = \frac{l_0}{h} \text{ and } \cos\alpha = \frac{l}{h} \tag{4}$$

$$\sin\alpha_0 = \frac{2 \cdot \pi \cdot r_0 \cdot n}{h} \text{ and } \sin\alpha = \frac{2 \cdot \pi \cdot r \cdot n}{h} \tag{5}$$

$$\frac{l}{l_0} = \frac{\cos\alpha}{\cos\alpha_0} \text{ and } \frac{r}{r_0} = \frac{\sin\alpha}{\sin\alpha_0} \tag{6}$$

$$r = r_0 \cdot \frac{\sqrt{1-\cos^2\alpha}}{\sin\alpha_0} = r_0 \cdot \frac{\sqrt{1-\left(\frac{l}{l_0} \cdot \cos\alpha_0\right)^2}}{\sin\alpha_0} \tag{7}$$

$$\frac{dr}{dl} = -\frac{r_0 \cdot l \cdot \cos^2\alpha_0}{l_0^2 \cdot \sin\alpha_0} \cdot \frac{1}{\sqrt{1-\left(\frac{l}{l_0} \cdot \cos\alpha_0\right)^2}} \tag{8}$$

$$F(p,\kappa) = p \cdot \pi \cdot r_0^2 \cdot (a \cdot (1-\kappa)^2 - b) \tag{9}$$

Where $a = \frac{3}{tg^2\alpha_0}$, $b = \frac{1}{\sin^2\alpha_0}$, $\kappa = \frac{l_0 - l}{l_0}$, $0 \le \kappa \le \kappa_{max}$, and V the muscle volume, F the pulling force, p the applied pressure, r_0, l_0, α_0 the initial inner radius and length of the PAM and the initial angle between the thread and the muscle long axis, r, l, α the inner radius and length of the PAM and angle between the thread and the muscle long axis when the muscle is contracted, h the constant thread length, n the number of turns of thread and κ the contraction.

Equation 9 is based on the admittance of a continuously cylindrical-shaped muscle. The fact is that the shape of the muscle is not cylindrical on the end, but rather is flattened, accordingly, the more the muscle contracts, the more its active part decreases, so the actual maximum contraction ration is smaller than expected [4].

Tondu and Lopez in [4] consider improving equation 9 with a correction factor (ε), on the one hand, it does not pay attention to the material that the muscle is made of, and on the other hand, it predicts for various pressures the same maximal contraction. This new equation is relatively good for higher pressure ($p \ge 2$ bar). Kerscher et al. in [5] suggest achieving similar approximation for smaller pressure another correction factor (μ) is needed, so the modified equation is:

$$F(p,\kappa) = \mu \cdot p \cdot \pi \cdot r_0^2 \cdot (a \cdot (1-\varepsilon \cdot \kappa)^2 - b) \tag{10}$$

Where $\varepsilon = a_\varepsilon \cdot e^{-p} - b_\varepsilon$ and $\mu = a_\kappa \cdot e^{-\kappa \cdot 40} - b_\kappa$.

The significant differences between the theoretical and experimental results were analyzed and proved in [6, 7, 8]. Therefore we have introduced a new approximation algorithm:

$$F(p,\kappa) = (a \cdot p + b) \cdot e^{(c \cdot \kappa + d)} + (e \cdot p + f) \cdot \kappa + g \cdot p + h \tag{11}$$

The unknown a, b, c, d, e, f, g and h parameters can be found using genetic algorithm.

The accuracy of equation 11 was demonstrated in [6, 7, 8], too.

3. Experimental Results

The precise positioning of PAMs requires accurate determination of the dynamic model of pneumatic actuators. Therefore the hysteresis in the tension-length (contraction) cycle of PAMs was analyzed.

Chou and Hannaford in [9] report hysteresis to be substantially due to Coulomb friction, which is caused by the contact between the bladder and the shell, between the braided threads and each other, and the shape changing of the bladder. Some experiments were made to illustrate the hysteresis (Figure 2).

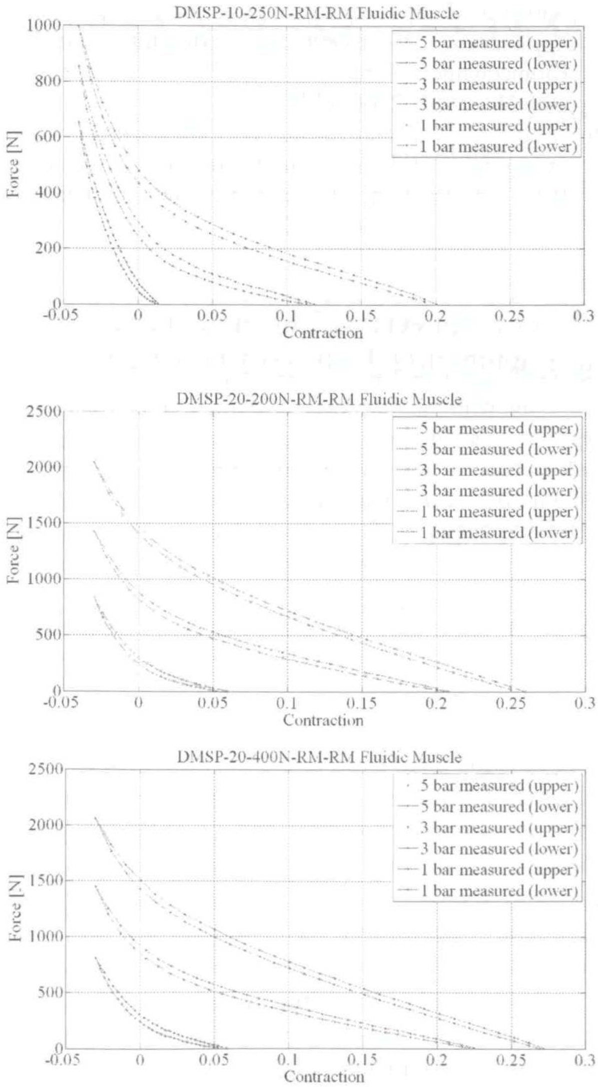

Figure 2 Hysteresis in the tension-length (contraction) cycle

The unknown parameters were found using genetic algorithm in Matlab environment (Figure 3).

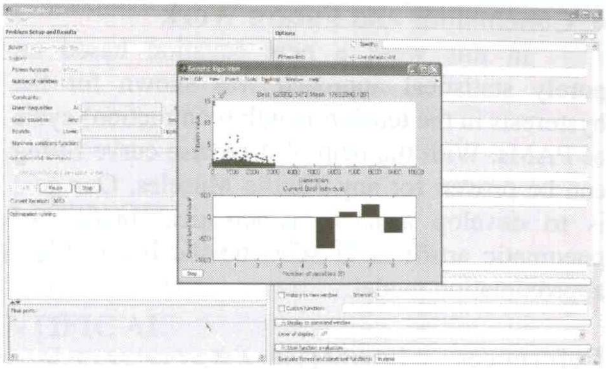

Figure 3 Determination of unknown parameters in Matlab environment

To prove versatility of equation 11, comparisons were done between the measured data and force model. The accurate fitting is demonstrated in Figure 4.

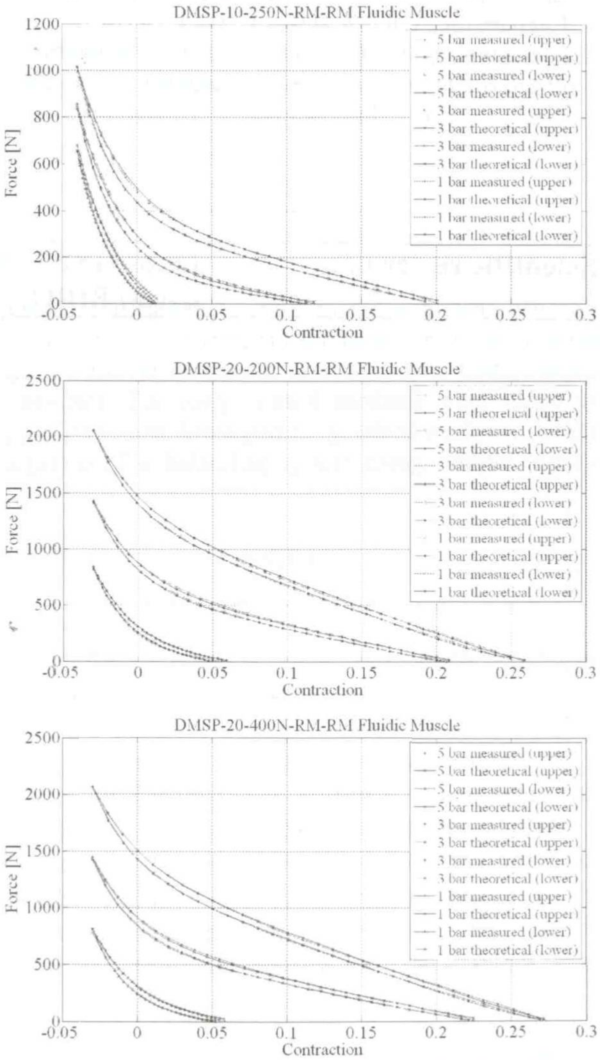

Figure 4 Approximation of hysteresis loop

4. Conclusions and Future Work

In this work a new equation based on purely statistical approach was shown for the hysteresis in the tension-length (contraction) cycle of PAMs. With the help of it precise curve fitting can be proven for any Fluidic Muscles. Our goal is to develop a new mathematical model for pneumatic artificial muscles on the basis of our approximation model.

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